COSMIC RAY SOURCE ABUNDANCES DERIVED FROM HIGH ENERGY MEASUREMENTS OF Fe-GROUP NUCLEI

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Abstract

We examine the cosmic ray source composition of elements from Ar to Ni ($18 \leq Z \leq 28$) using data from ~0.1 to ~200 GeV/nuc and a cosmic ray propagation code that includes improved fragmentation cross-sections. By fitting available satellite data over more than three decades in energy/nuc, including recent HEAO-3 data, we obtain improved source abundances for Ar, Ca, Cr, Mn, and Ni, and compare these with recent determinations of the solar composition. We find no evidence for an energy-dependent source composition below ~20 GeV/nuc, but the data at higher energies deserve further study.

Introduction: Although Fe (Z=26) is the dominant cosmic ray element in the range from Ar to Ni (Z = 18 to 28), five elements (Ar, Ca, Cr, Mn, and Ni) might be expected to have source abundances ranging from ~1% to 10% of Fe. Earlier studies of the galactic cosmic ray source (GCRS) composition [see, e.g., Dwyer and Meyer (1985), and reviews by Mewaldt (1983), and Simpson (1983)] have reported finite source abundances for Ca, Ni (and sometimes Ar), with typical uncertainties ranging from ~20% to 70%. For Cr and Mn only upper limits to the source abundance were typically obtained, because of cross section uncertainties and large secondary contributions to the observed abundance of these elements (see, e.g., Hinshaw and Wiedenbeck 1983). Using improved cross sections in conjunction with a complete propagation/solar-modulation code to fit satellite data from ~0.1 to >100 GeV/nuc, we obtain improved determinations of the source abundances of Fe-group elements, examining in particular the composition at the highest energies.

Cosmic Ray Measurements: The cosmic ray measurements in this study are mainly from HEAO-3, including "low-energy" (0.5 to 1.1 GeV/nuc) and recently revised "high-energy" (10 to 200 GeV/nuc) data from HEAO-C3, and recently revised 0.8 to 35 GeV/nuc data from the HEAO-C2 experiment. We also used lower energy data from IMP-8 and from Voyager-2 near 22 AU. The high-energy HEAO-C3 data were reported as abundances relative to Fe in energy intervals that differ from element to element. We corrected the abundances to common energy/nuc intervals (corrections typically <5%) using the reported energy dependence (Vylet et al. 1990). In addition, we estimated the "secondary/primary" ratio (Sc+Ti+V)/Fe at the highest energies by scaling from the reported Ti/Fe ratio, assuming that the relative abundances of Sc at >120 GeV/nuc and V at >40 GeV/nuc are the same as at lower energies.

Propagation Model: This analysis is based on the standard "leaky-box" model with a rigidity-dependent escape-length from the galaxy of $\lambda_e = 24.9\beta R^{-0.6}$ g/cm^2 for rigidities >4.0 GV, and $\lambda_e = 10.8\beta$ g/cm^2 for R < 4 GV, a dependence originally designed to fit B/C. All species are assumed to have identical source spectra that are power laws in rigidity with index -2.3. Solar modulation corrections use the "force-field" approximation with a modulation factor $\Phi = 600(Z/A)$ MeV/nuc. The propagation code is based on that used by the Saclay group (Soutoul et al. 1985), and includes the effects of nuclear fragmentation, radioactive decay, and ionization energy-loss. The cross sections include extensive recent measurements by the UNH group along with a new semi-empirical program to predict unmeasured cross sections (Webber 1989). We also included the effects of electron pickup and subsequent electron-capture decay for nuclei such as ^{51}V, ^{54}Mn, and ^{55}Fe.

Approach: To measure secondary production we use the ratio (Sc+Ti+V)/Fe (Figure 1), since Sc, Ti, and V should all be essentially absent in GCRS material [(Sc+Ti+V)/Fe < 0.004 in the solar system]. Note that the assumed λ_e fits this ratio over ~3 decades in energy/nuc. Starting with an assumed "solar system" elemental and isotopic composition we then adjusted the source abundances of Ar, Ca, Cr, Mn, and Ni to fit the observations.

Figures 2 thru 5 show abundances relative to Fe for various assumed source compositions. It is also interesting to consider abundances relative to the Sc+Ti+V secondaries (see example in Figure 6). In such abundance ratios propagation uncertainties tend to cancel, and at the highest energies these ratios are very sensitive to the source abundance of relatively rare elements such as Ar and Cr.

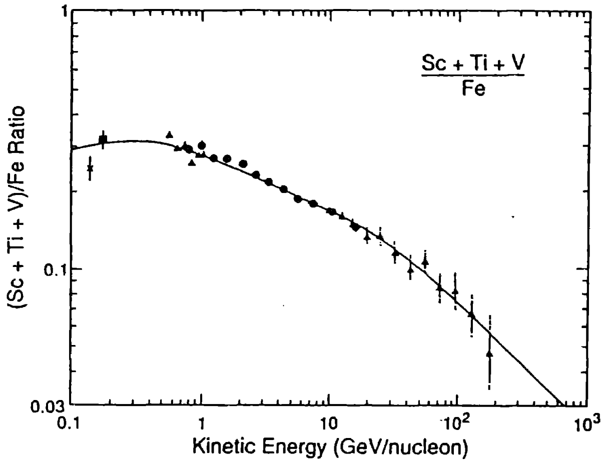

Figure 1: A fit to the (Sc+Ti+V)/Fe ratio using the leaky box model with a rigidity-dependent pathlength distribution (see text). References to the measurements: triangles (HEAO-C3; Jones 1985, Binns et al. 1988; Vylet et al. 1990); circles (HEAO-C2; Engelmann et al. 1989); square (IMP-8; Simpson 1983); cross (Voyager-2; Ferrando et al. 1989); Dotted extensions to the HEAO-C2 points indicate possible systematic errors. The "break" at ~25 GeV/nuc is discussed in the text.

The Figures reveal that from ~0.1 to ~20 GeV/nuc the Ar, Ca, and Cr measurements can be fit with a single energy-independent source composition. It is clear that non-zero source abundances are required at all energies for Ar, Ca, and Cr. For Cr the fit is reasonable to the very highest energies (~200 GeV/nuc), while for Ar and Ca the >20 GeV/nuc data suggest an enhanced source abundance. While this apparently energy-dependent source composition may result from a systematic effect in the HEAO-C2 data (Binns et al. 1988), the highest-energy HEAO-C2 point is consistent with this trend. Cross section variations with energy of 50% to 100% would be required to account for this effect.

For each of the data points in Figures 2 to 5 we derived a source abundance using the Sc+Ti+V observations at the same energy to "trace" the secondary contributions. Table 1 summarizes the mean values of these determinations (at this point still preliminary) based on data from 0.1 to 20 GeV/nuc. For energies >20 GeV/nuc, we find Ar/Fe $\simeq$ 0.03 and Ca/Fe $\simeq$ 0.07. The quoted uncertainties are dominated by an assumed 5% uncertainty in the *relative* cross sections for production of various elements from Fe. The uncertainties (once final) will be several times smaller than those from an analysis of HEAO-C2 data using semi-empirical cross-sections with ~35% accuracy (Hinshaw and Wiedenbeck 1983). The Ni abundance was derived from a similar analysis (see also Binns et al. 1988).

Mn is a special case because ^{54}Mn can decay by β^--emission with a half-life estimated at ~4x10^4 years to ~10^7 years. These calculations assume a GCRS ratio of Mn/Fe = 0.0106, as in the solar system, a ^{54}Mn half-life of 2 x 10^6 years (Koch et al., 1981; Grove et al. 1990), and an interstellar H density of 0.3 cm^{-3}. A lower limit to the source ratio of Mn/Fe = 0.006 $\pm$ 0.006 results from assuming no ^{54}Mn decay, while an upper limit of Mn/Fe = 0.030$\pm$0.006 results from assuming the Sur et al. (1989) lower limit to the half-life of 4x10^4 years. Our adopted source abundance covers these possibilities.

Discussion: In a previous analysis of HEAO data Binns et al. (1988) concluded that the abundances of the secondary elements K, Sc, Ti, and V relative to Fe generally decreased as power laws in energy/nuc with exponents $\simeq$ -0.3. Our analysis shows that the leaky-box model predicts a "break" in the energy dependence of secondary/primary ratios such as (Sc+Ti+V)/Fe at an energy (E_B) where $\lambda_e(E_B) \simeq \lambda_i$, where λ_i is the nuclear interaction mean free path (~2.2 g/cm^2 for Fe). Taking λ_e=λ_i=2.2 g/cm^2 we find E_B(GeV/nuc) $\simeq$ (Z/A)R_B(GV) = (Z/A)$(24.9\beta/2.2)^{1.67}$ $\simeq$ 27 GeV/nuc. For E<E_B loses are dominated by escape from the confinement region, while for E>E_B losses due to nuclear interactions dominate. The evidence for an apparent break in Figure 1 can be taken as confirmation of models that employ an exponential distribution of pathlengths. Binns et al. (1988) derived

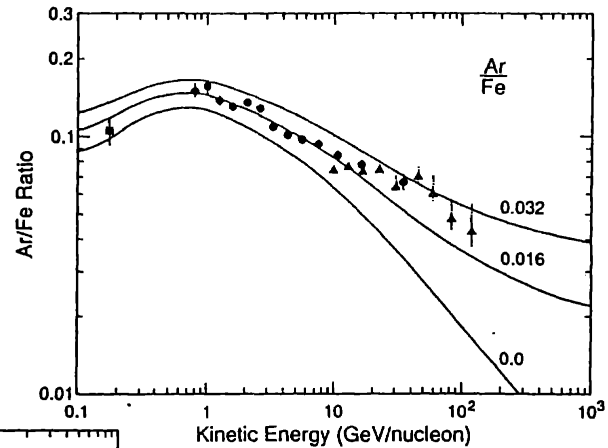

Figure 2: Measured and calculated Ar/Fe ratios. The curves are labeled by the assumed source values for Ar/Fe. For references to the data see Figure 1.

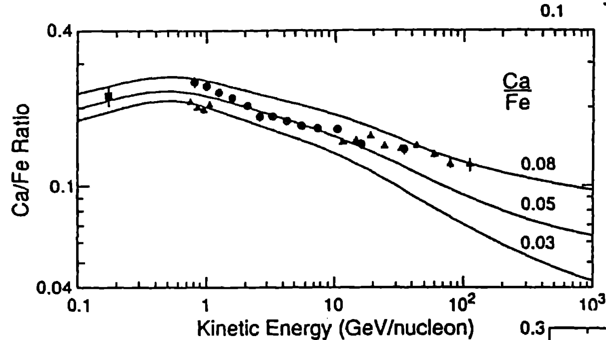

Figure 3: Same as Figure 2, but for Ca/Fe.

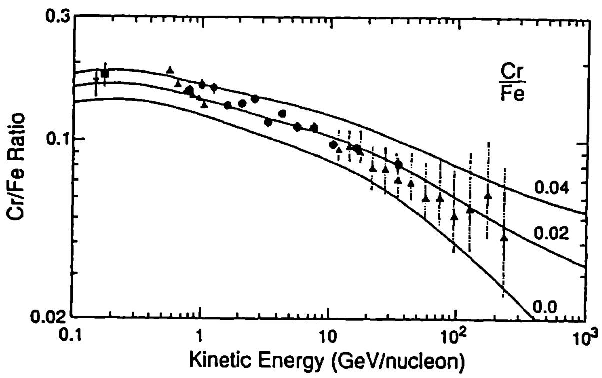

Figure 4: Same as Figure 2, but for Cr/Fe.

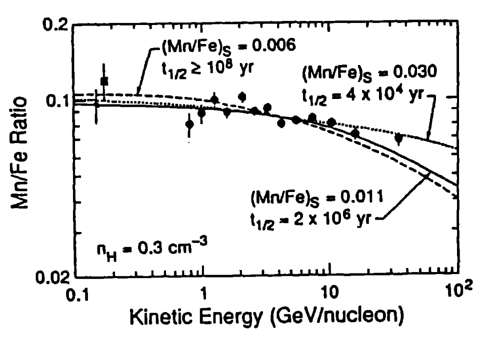

Figure 5: Same as Figure 2, but for Mn/Fe. The calculated curves are labeled by the assumed half-life against β^- emission for ^{54}Mn, assuming an interstellar H density of 0.3 cm^{-3}.

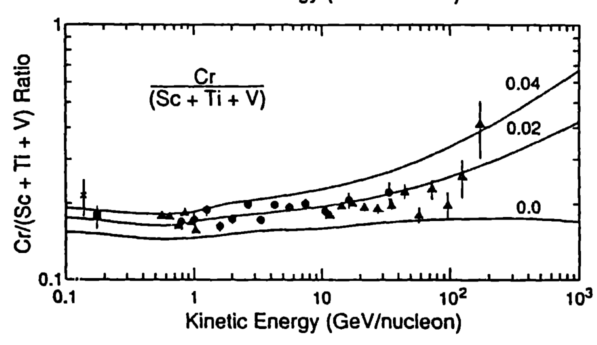

Figure 6: Plot of the Cr/(Sc+Ti+V) ratio vs. energy/nuc. The curves are labeled with the assumed source values for Cr/Fe. See Figure 1 for references to the data points.

Table 1: Fe-Group Composition

Element	GCR Source (This Work)	Solar Photosphere[2]	Meteorites[2]	SEP-Derived Corona[3]
Ar	0.019 ± .006	(0.078 ± .019)	(0.078 ± .019)	0.019 ± .004
Ca	0.055 ± .010	0.049 ± .004	0.068 ± .005	0.065 ± .013
Cr	0.024 ± .006	0.0100 ± .0010	0.0148 ± .0011	0.014 ± .003
Mn	0.018 ± .018	0.0052 ± .0005	0.0106 ± .0010	0.005 ± .003
Fe	≡1.00	≡1.00	≡1.00	≡1.00
Ni	0.055 ± .005	0.038 ± .004	0.055 ± .003	0.037 ± .006

1) Note that the three solar system compositions are in some cases interdependent. Parentheses are used to indicate especially uncertain values.
2) Anders and Grevesse (1989).
3) Breneman and Stone (1985).

abundances from essentially the same HEAO data assuming a simple semi-empirical representation of the data. Our lower abundances of Ar and Ca likely result from our use of a more sophisticated propagation model (see also Vylet et al. 1990).

Table 1 also summarizes recent solar system compositions, including meteoritic and photospheric material, and coronal material as derived from solar energetic particles (SEPs). The low Ar value in both GCR and coronal material is consistent with its low first ionization potential. While there is generally good agreement between the GCRS and solar system values, it is interesting that the present measurements suggest that GCRS Cr may be enhanced with respect to the solar system by a factor of $\sim$1.6±0.4, since an enhancement might be expected from "supermetallicity" models (e.g., Mewaldt et al. 1980). There is also a significant difference between GCRS and coronal Ni.

In summary, we find that new cross sections lead to significantly improved fits to the observations over a broad energy interval. There is presently no evidence for an energy dependent source composition up to at least 20 GeV/nuc. At higher energies, where cosmic rays have traversed only an average of $\sim$1g/cm^2 or so and the sources become almost "bare", the observations are in principle more sensitive to the source composition. While the present study suggests enhanced abundances of Ar and Cr at higher energies, these require further study, and it will probably require new instrumentation such as Astromag to more fully exploit the potential of high-energy spectroscopy.

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